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6. AUTHORS Robert McDermott, Clare Yu, John Martinis		5d. PROJECT NUMBER		
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14. ABSTRACT Qubit dephasing is governed by low-frequency noise in the bias parameters that control the energy separation between the qubit states. It has been shown that dephasing in phase and flux qubits is dominated by an excess low frequency magnetic flux noise with a 1/f power spectrum and magnitude at 1 Hz of order 1 microPhi0/sqrt(Hz). Recent experiments by McDermott et al. provide clear evidence for the existence of unpaired magnetic states on the surfaces of superconducting thin film devices; it is now believed that fluctuations of these surface spin states are the source of the ubiquitous 1/f flux noise. However, the microscopic mechanism that drives fluctuations of these spins				
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Report Title

Final Report: Decoherence from 1/f Flux Noise

ABSTRACT

Qubit dephasing is governed by low-frequency noise in the bias parameters that control the energy separation between the qubit states. It has been shown that dephasing in phase and flux qubits is dominated by an excess low frequency magnetic flux noise with a 1/f power spectrum and magnitude at 1 Hz of order 1 microPhi0/sqrt(Hz). Recent experiments by McDermott et al. provide clear evidence for the existence of unpaired magnetic states on the surfaces of superconducting thin film devices; it is now believed that fluctuations of these surface spin states are the source of the ubiquitous 1/f flux noise. However, the microscopic mechanism that drives fluctuations of these spins is not understood; moreover, there is no clear path to reducing the flux noise magnitude. This program is devoted to a systematic investigation of magnetic surface defects in SQUIDs and phase qubits. Measurements of surface spin susceptibility and susceptibility noise will yield valuable clues about the microscopic nature of the magnetic fluctuators, and shed light on interactions between defects. The role of qubit loop geometry on flux noise magnitude and dephasing will be explored in detail. The experiments will guide theoretical efforts to develop improved models for flux noise.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
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- 05/07/2014 4.00 R. Barends, Radoslaw C. Bialczak, Yu Chen, J. Kelly, M. Lenander, Daniel Sank, E. Lucero, Matteo Mariantoni, A. Megrant, M. Neeley, P. J. J. O'Malley, A. Vainsencher, H. Wang, J. Wenner, T. C. White , T. Yamamoto, Yi Yin, A. N. Cleland, John M. Martinis. Flux Noise Probed with Real Time Qubit Tomography in a Josephson Phase Qubit,
Physical Review Letters, (08 2012): 1067001. doi:
<https://doi.org/10.1103/PhysRevLett.106.1067001>
- 05/07/2014 5.00 Jiansheng Wu, Clare Yu. Modeling Flux Noise in SQUIDs due to Hyperfine Interactions,
PHYSICAL REVIEW LETTERS, (06 2012): 1247001. doi:
<https://doi.org/10.1103/PhysRevLett.108.1247001>
- 08/30/2012 1.00 Jiansheng Wu, Clare Yu. How stress can reduce dissipation in glasses,
Physical Review B, (11 2011): 0. doi: 10.1103/PhysRevB.84.174109
<https://doi.org/10.1103/PhysRevB.84.174109>
- 08/30/2012 2.00 Clare Yu, Jiansheng Wu. Modeling Flux Noise in SQUIDs due to Hyperfine Interactions,
Physical Review Letters, (06 2012): 0. doi: 10.1103/PhysRevLett.108.247001
<https://doi.org/10.1103/PhysRevLett.108.247001>
- 08/30/2012 3.00 Daniel Sank, R. Barends, Radoslaw Bialczak, Yu Chen, J. Kelly, M. Lenander, E. Lucero, Matteo Mariantoni, A. Megrant, M. Neeley, P. O'Malley, A. Vainsencher, H. Wang, J. Wenner, T. White, T. Yamamoto, Yi Yin, A. Cleland, John Martinis. Flux Noise Probed with Real Time Qubit Tomography in a Josephson Phase Qubit,
Physical Review Letters, (08 2012): 0. doi: 10.1103/PhysRevLett.109.067001
<https://doi.org/10.1103/PhysRevLett.109.067001>

TOTAL: **5**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

1. C.C. Yu, "Noise in Superconducting Qubits and Spin Glasses" UC Irvine Physics Department Colloquium, Jan. 2012
2. S. Sendelbach, "Investigation of 1/f Flux Noise in Superconducting Circuits", APS March Meeting 2012, Boston, MA
3. R. McDermott, "1/f Flux Noise and Dephasing in Superconducting Circuits", June 2012, Chernogolovka, Russia
4. R. McDermott, "Dephasing from 1/f Flux Noise," Aug. 2012 seminar, UC Santa Barbara.
5. C.C. Yu, "Noise in Superconducting Qubits," Sept. 2012 colloquium, University of Central Florida.
6. C.C. Yu, "Noise in Superconducting Qubits," Sept. 2012 seminar, UC-Berkeley.
7. T. Klaus, "Investigations of 1/f Flux Noise in SQUIDs and Superconducting Qubits," 2013 APS March Meeting talk, Baltimore.
8. C.C. Yu, "Noise in Superconducting Qubits and Spin Glasses," Jun. 2013 invited talk, International Conference on Noise and Fluctuations, Montpellier, France.
9. P. Kumar, "1/f flux noise and field-dependent spin susceptibility", 2014 APS March Meeting talk, Denver.
10. C. Shi, "Simulation of the magnetism of the 2D XY spin system in finite magnetic field", 2014 APS March Meeting talk, Denver.

Number of Presentations: 10.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received

Book Chapter

TOTAL:

Patents Submitted

Suppression of magnetically active surface defects in superconducting integrated circuits

Patents Awarded

Awards

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Peter O'Malley	0.43	
Daniel Sank	0.18	
Thomas Hinkle	0.05	
Jacob Podkaminer	0.16	
Steven Sendelbach	0.19	
Christopher Wilen	0.15	
Ed Leonard	0.08	
Babita Yadav	0.09	
FTE Equivalent:	1.33	
Total Number:	8	

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Jiansheng Wu	0.25
Umeshkumar Patel	0.01
Sungho Han	0.25
Chuntai Shi	0.50
Ted Thorbeck	0.19
Pradeep Kumar	0.25
FTE Equivalent:	1.45
Total Number:	6

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT_SUPPORTED</u>	National Academy Member
John Martinis	0.00	
Robert McDermott	0.05	
Clare Yu	0.00	
FTE Equivalent:	0.05	
Total Number:	3	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT_SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

<u>NAME</u>
Steven Sendelbach
Daniel Sank
Total Number:

2

Names of other research staff

<u>NAME</u>	<u>PERCENT_SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

WISCONSIN:

The Wisconsin group has made an identification of the dominant sources of magnetism in superconducting integrated circuits and developed strategies for suppressing this magnetism. They submitted two successful user proposals to the Advanced Photon Source at Argonne National Laboratory, where they performed experiments using X-ray Magnetic Circular Dichroism (XMCD) to probe magnetism at the surfaces of Nb and Al thin films. XMCD is a spectroscopic technique that is both element-specific and sensitive to magnetism. The experiments showed no evidence of magnetism in native Al and Nb thin films cooled to low temperature in an ultra-high vacuum (UHV) environment; however, when the films were cooled to low temperature in a degraded vacuum environment, both Al and Nb films showed a strong magnetic signature at the oxygen K-edge. Subsequent density functional theory modeling by the Irvine group confirmed that the measured signal was due to molecular O₂. It is likely that adsorbed molecular O₂ is the source of the low-frequency flux noise, and that improvements in the vacuum environment of the sample will lead to a suppression of the noise. Earlier on in this program, the Wisconsin group demonstrated a significant noise reduction for SQUID devices encapsulated in silicon nitride as opposed to silicon oxide. This observation is compatible with adsorbed oxygen as the microscopic source of the noise, as the energetics of spin reorientation are very different for O₂ adsorbates on a nitride surface compared to a an oxide surface, as pointed out by the Irvine group: it is expected that the O₂ moments will freeze out on an nitride surface at a relatively high temperature of a few hundred millikelvin, while they remain magnetically active to low temperatures on an oxide surface. In a series of follow-up experiments, the Wisconsin group found that the magnetic signature for samples dosed with either air or pure O₂ is similar; this is understood as due to the fact that the solubility of molecular nitrogen in solid molecular O₂ is very low. For a sample cooled in a degraded vacuum with pressure higher than about 10-8 Torr, adsorption of O₂ begins to take place around 45 K. The Wisconsin group is in the process of working with the Irvine theory group to extract a fractional surface coverage of O₂ from the measured X-ray absorption signals. In parallel work, they have performed SQUID-based susceptibility measurements and noise measurements to evaluate the effect of different vacuum environments and cooldown protocols on magnetism from surface spins and on device noise. They have found that UV irradiation of the sample during cooldown can reproducibly and reversibly alter the zero-frequency susceptibility of the surface spin system at the ~ 30% level. In a separate experiment, they have suppressed the surface spin susceptibility by a factor of 3 by enclosing the sample in an evacuated hermetic cell and passivating the device with weakly electrophilic NH₂ adsorbates. They have developed an optimized hermetic sample enclosure incorporating all-welded electrical feedthroughs and a single conflat flange, and have found that a sample that is baked in this cell shows a very different zero-frequency susceptibility, with a diverging susceptibility at around 150 mK that suggests a magnetic phase transition. They are in the process of measuring flux noise in this cell. Finally, they have begun to investigate possible magnetic contributions to high-frequency loss. For a typical coplanar geometry, the magnetic participation ratio of a ~ 1 nm layer of adsorbed molecular oxygen is around 10-4, of the same order as the dielectric participation ratio of a ~ 1 nm-thick interfacial layer between the metal and the substrate, so magnetic loss in the adsorbed spin system could act as a significant depolarizing channel. Previous work by the group indicates coupling of the Josephson oscillations in a SQUID circuit to low-frequency spin susceptibility. They have designed hermetic sample boxes that are compatible with both resonator and qubit measurements, and construction of these enclosures should be completed in early January. The Wisconsin group is preparing two papers on the work conducted under this program over the past 4 years.

IRVINE:

Clare Yu has collaborated with Ruqian Wu, an expert in density functional theory (DFT), to understand the microscopic origin of flux noise. Using DFT, they showed that oxygen molecules adsorbed on the surfaces of devices are the likely source of flux noise. Oxygen molecules have a sizeable magnetic dipole moment of about 2 μ B. They find that an oxygen molecule adsorbed on a sapphire surface has a very small energy barrier of 12 mK to spin reorientation, making it easy for thermal spin flips to occur. They have done Monte Carlo simulations indicating that exchange coupling between the spins broadens the distribution of spin flip times and leads to 1/f magnetization (flux) noise. A preprint on this work is in preparation. In addition, they have provided theoretical support for the XMCD measurements done by the Wisconsin group. For oxygen, the spin-orbit coupling produces an energy level splitting in the pi-orbitals so that electronic transitions from the sigma orbital to the pi orbital produced by absorbing left-circularly polarized light are different from transitions produced by absorbing right-circularly polarized light. By taking the difference between the absorption spectra of right and left circularly polarized light taken in a magnetic field, one can obtain the spin and orbital magnetic moment of oxygen. The Irvine group used DFT to do XMCD calculations on a free oxygen molecule and find very good agreement with recent results from the experimental team. Finally, the Irvine group used DFT to examine whether vacancies, e.g., O, Al, Al-O-O, or Al-O vacancies, could be the source of flux noise. An oxygen vacancy has a tiny magnetic moment and an Al-O-O tri-vacancy has a large formation energy (> 5 eV). Al and Al-O vacancies have sizable magnetic moments in sapphire, but this moment disappears in gamma-alumina which is closer to native aluminum oxide. In general, they find that vacancies are very sensitive to their local environment, e.g., the charge of the vacancy. Thus it is unlikely that vacancies are the source of flux noise.

UCSB:

The Santa Barbara group developed a method for measuring dephasing in experimental quantum systems based on randomized benchmarking that excels at measuring small levels of phase noise at the timescales relevant to gates for the surface code. They find that an Xmon qubit incorporating a SQUID loop is not limited by 1/f flux noise. Instead they observe a previously unreported telegraph noise mechanism. They demonstrate that full understanding of dephasing allows for the use of

"mediocre clocks"—systems with correlated phase noise—as good qubits.

Technology Transfer